Infrared Imaging of Exoplanets

William C. Danchi

January 5, 2012

ExoPAG #7

In 2009 we had the Exoplanet Community Report:

The exoplanet community's top priority is that a line of probe-class missions for exoplanets be established, leading to a flagship mission at the earliest opportunity.

The Infrared Chapter:

4 Infrared Imaging

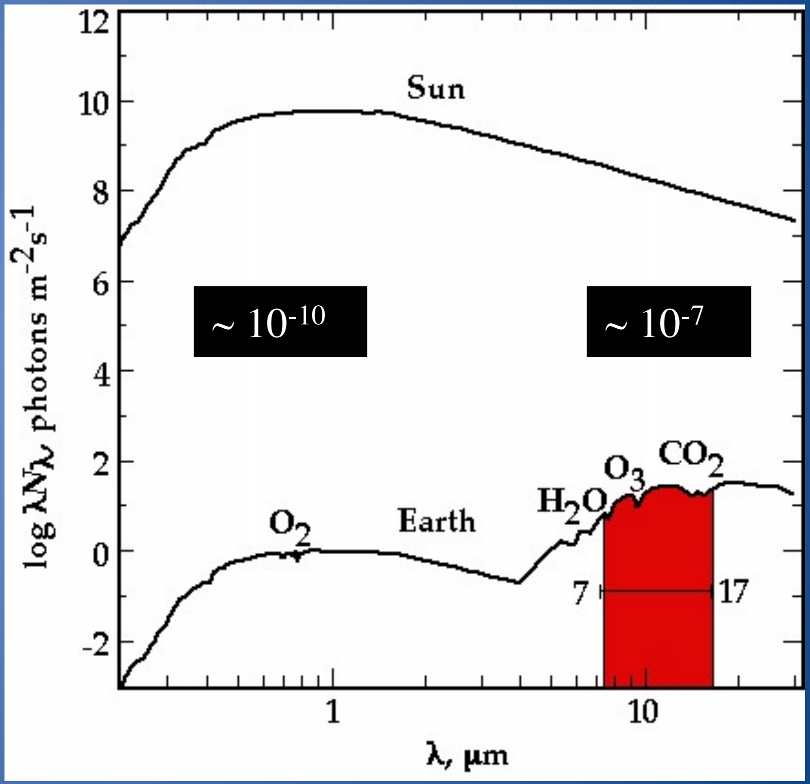
William Danchi, NASA Goddard Space Flight Center, Chair

Peter Lawson, Jet Propulsion Laboratory, Co-Chair

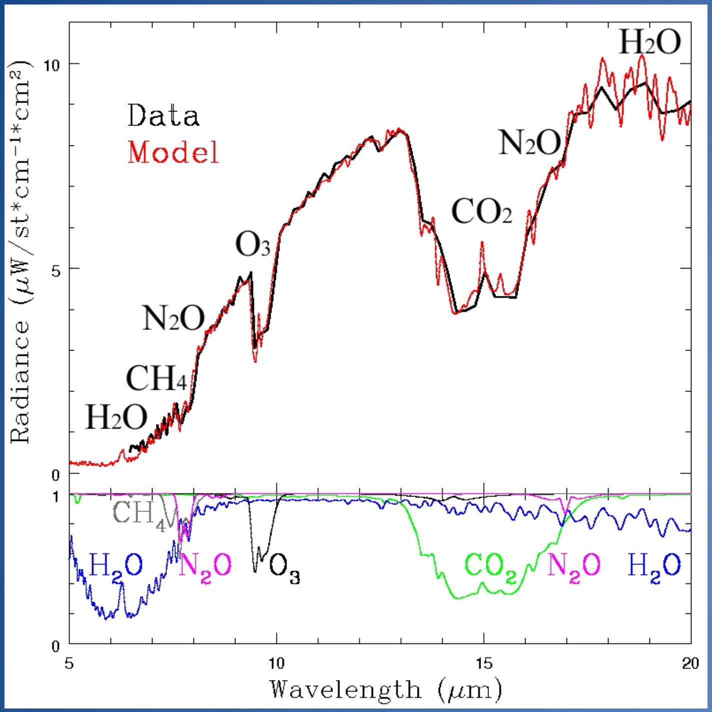
Olivier Absil, Rachel Akeson, John Bally, Richard K. Barry, Charles Beichman, Adrian Belu, Mathew Boyce, James Breckinridge, Adam Burrows, Christine Chen, David Cole, David Crisp, Rolf Danner, Peter Deroo, Vincent Coudé du Foresto, Denis Defrère, Dennis Ebbets, Paul Falkowski, Robert Gappinger, Ismail D. Haugabook, Sr., Charles Hanot, Thomas Henning, Phil Hinz, Jan Hollis, Sarah Hunyadi, David Hyland, Kenneth J. Johnston, Lisa Kaltenegger, James Kasting, Matt Kenworthy, Alexander Ksendzov, Benjamin Lane, Gregory Laughlin, Oliver Lay, Réne Liseau, Bruno Lopez, Rafael Millan-Gabet, Stefan Martin, Dimitri Mawet, Bertrand Mennesson, John Monnier, Naoshi Murakami, M. Charles Noecker, Jun Nishikawa, Meyer Pesesen, Robert Peters, Alice Quillen, Sam Ragland, Stephen Rinehart, Huub Rottgering, Daniel Scharf, Eugene Serabyn, Motohide Tamura, Mohammed Tehrani, Wesley A. Traub, Stephen Unwin, David Wilner, Julien Woillez, Neville Woolf, and Ming Zhao

Detecting Earth-area Planets is Difficult and the Thermal Infrared is a Good Spectral Region

- Detecting light from planets beyond solar system is hard:
  - Earth sized planet emits few photons/sec/m^2 at 10 µm
  - Parent star emits 10^6 more
  - Planet within 1 AU of star
  - Exozodi dust emission in target solar system x 300 brighter than earth-area planet for equivalent of *ONE* Solar System Zodi



Earth Spectrum Peaks in the mid-IR

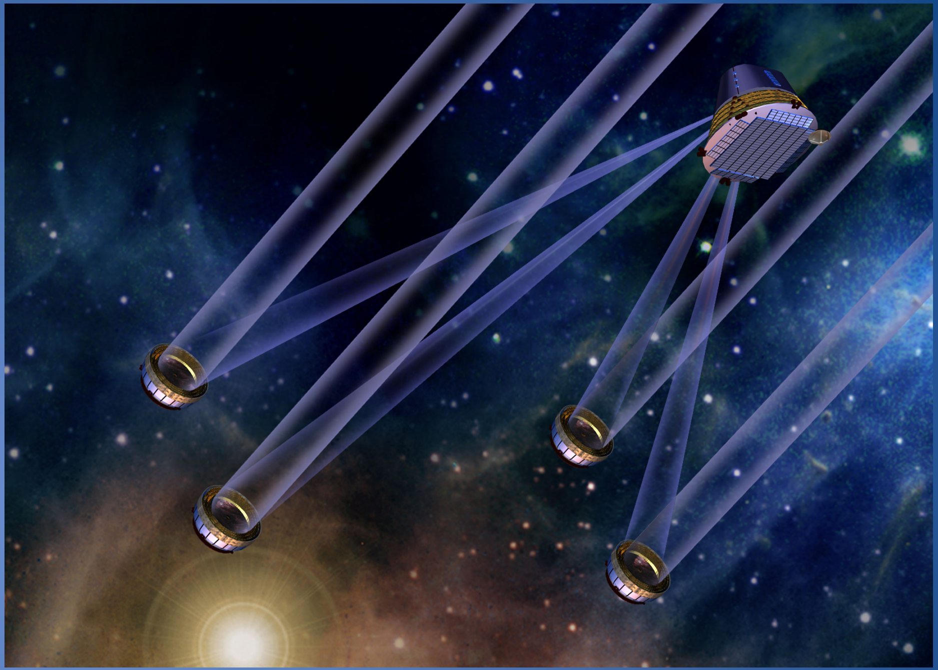


Earth's spectrum shows absorption features from many species, including ozone, nitrous oxide, water vapor, carbon dioxide, and methane

Biosignatures are molecules out of equilibrium such as oxygen, ozone, and methane or nitrous oxide.

Spectroscopy with R ~ 50 is adequate to resolve these features.

Terrestrial Planet Finder Interferometer



Salient Features

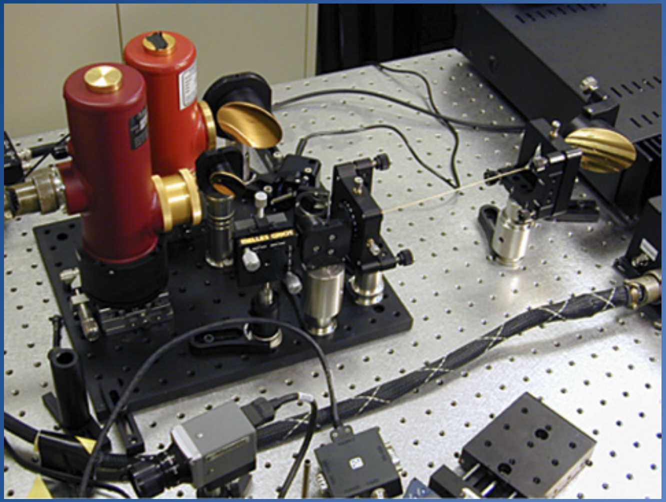
- Formation flying mid-IR nulling Interferometer
- Starlight suppression to 10^{-5}
- Heavy launch vehicle
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency

Science Goals

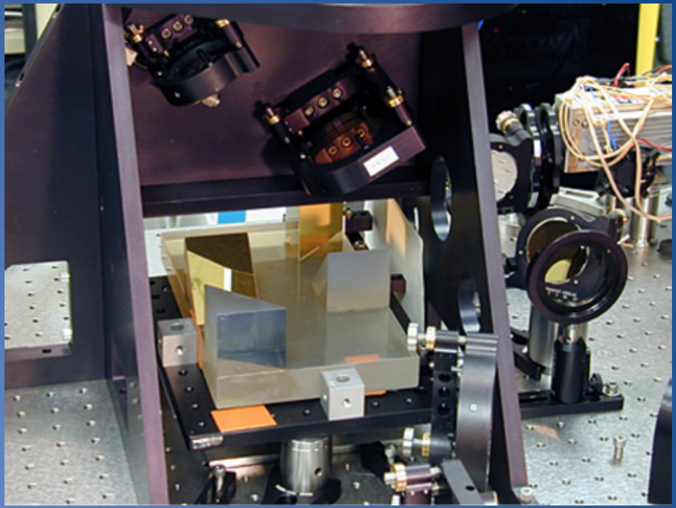
- Detect as many as possible Earth-like planets in the habitable zone of nearby stars via their thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as O_2, CO_2, CH_4 and H_2O
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics investigations as capability and time permit

W. C. Danchi, P.R.Lawson

Laboratory Testbed Milestones



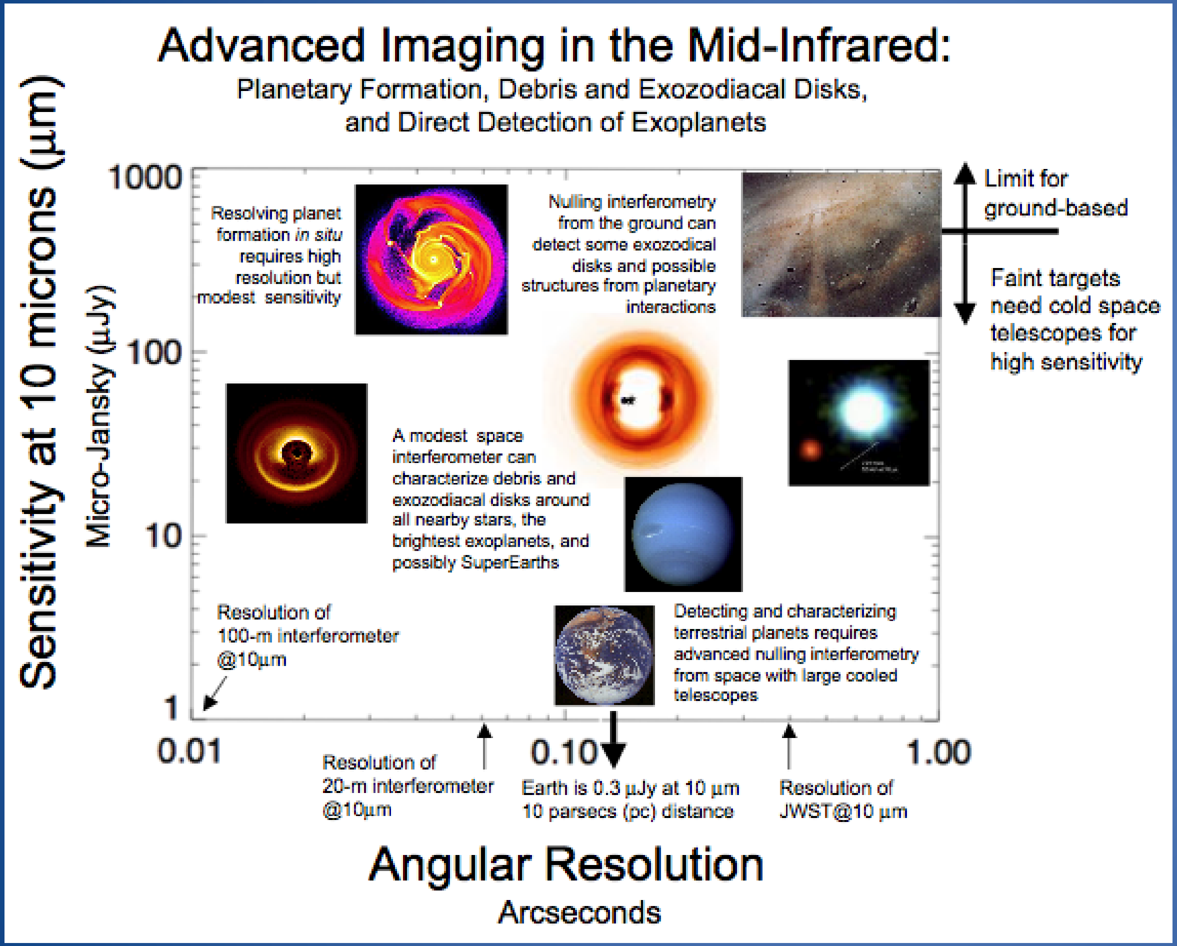
View of a chalcogenide glass fiber, in use within the Adaptive Nuller testbed. The fiber can be seen being fed by an off-axis parabola, to the right, prior to the spectrometer and single-pixel detector.



Side view of the periscope assembly of the Achromatic Nulling Testbed.

- MILESTONE #1 – Compensation of intensity and phase demonstrated by Adaptive Nuller testbed. Intensity compensated to 0.2% and phase to 5 nm rms across a 3 μm band centered at 10 μm
- MILESTONE #2 – Demonstration of precision formation flying maneuvers in a ground-based robotic testbed, with traceability to flight
- MILESTONE #3 – Demonstration of broadband nulling at the flight requirements of 1.0×10^{-5}, using 34% bandwidth centered at 10 μm. Monochromatic nulls demonstrated to 5×10^{-7}.
- MILESTONE #4 – Laboratory demonstration of detection of planet signal 10^6 times fainter than a star while using array rotation, chopping, and averaging.

Sensitivity and Resolution in the Mid-IR



Ground-based interferometry in the IR:

- Limited sensitivity
- Long baselines available
- Good for studying protoplanetary disks

Space-based interferometry:

1. Structurally Connected interferometer (limited baseline length)

- Exozodi levels for ALL TPF/Darwin stars
- Debris Disks
- Characterize Warm & Hot Planets & Super Earths

2. Formation-flying or tethers (long baselines)

- Detect and characterize many Earth-sized planets
- Transformational astrophysics

Observations and some findings

•Advanced imaging with both high-angular resolution and high sensitivity in the mid-infrared is essential for future progress across all major fields of astronomy.

•Exoplanet studies particularly benefit from these capabilities.

•Thermal emission from the atmospheric and telescope(s) limits the sensitivity of ground-based observations, driving most science programs towards space platforms.

•Even very modest sized cooled apertures can have orders of magnitude more sensitivity in the thermal infrared than the largest ground-based telescopes currently in operation or planned.

•We find a mid-IR interferometer with a nulling capability on the ground and a connected-element space interferometer both enable transformative science while laying the engineering groundwork for a future "Terrestrial Planet Finder" space observatory requiring formation-flying elements.

Our main recommendations:

Although we support most of the long-term goals that the Exoplanet Task Force (ExoPTF) recommended for a flagship infrared mission, we recommend a different path forward for the near-term. Specifically, we are not convinced, as the ExoPTF report suggests, that the problem of exozodi levels and debris disks can be solved with ground-based observations to the extent necessary for the formulation of a flagship mission. We are not convinced, in part due to our own experience with the Keck Interferometer, for which the lower limit on exozodis is 100–200 times that of the Solar System zodi level. We expect that the nulling instrument on Large Binocular Telescope Interferometer (LBTI) will reduce this limit substantially for a relatively small sample of stars. We discuss how a probe-class mission in the infrared can measure the exozodi levels down to the level of one Solar System zodi for essentially *all* of the potential target stars for the eventual flagship TPF/Darwin missions. This step is crucial, not only for the flagship characterization missions, but is also of great value to an astrometric mission because that mission can then focus its searches for Earth-twins around stars with low exozodi levels. Moreover, an infrared probe-class mission has a higher degree of technology leveraging from *JWST*, and could be undertaken in a relatively short time without undue cost and technology risk. Our summary of recommendations from this chapter follows:

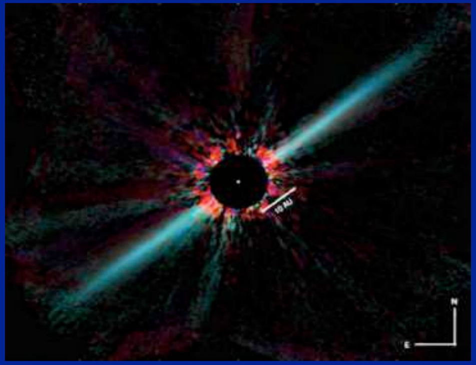
Recommendation: A vigorous technology program, including component development, integrated testbeds, and end-to-end modeling, should be carried out in the areas of formation flying and mid-infrared nulling, with the goal of enabling a probe-scale nulling interferometry mission in the next 2 to 5 years and a flagship mission within the next 10 to 15 years.

Recommendation: The fruitful collaboration with European groups on mission concepts and relevant technology should be continued.

Recommendation: R&A should be supported for the development of preliminary science and mission designs. Ongoing efforts to characterize the typical level of exozodiacal light around Sun-like stars with ground-based nulling interferometry should be continued.

Astro2010
Research & Analysis Recommendations

- ***Ground-based interferometry***
  - *Ground-based interferometry serves critical roles in exoplanet studies. It provides a venue for development and demonstration of precision techniques including high contrast imaging and nulling, it trains the next generation of instrumentalists, and develops a community of scientists expert in their use.*
  - *We endorse the recommendations of the "Future Directions for Interferometry" Workshop and the ReSTAR committee report to continuing vigorous refinement and exploitation of existing interferometric facilities (Keck, NPOI, CHARA and MRO), widening of their accessibility for exoplanet programs, and continued development of interferometry technology and planning for a future advanced facility*
  - *The nature of Antarctic plateau sites, intermediate between ground and space in potential, offers significant opportunities for exoplanet and exozodi studies by interferometry and coronagraphy.*
- ***Space-based Interferometry***
  - *Space-based interferometry serves critical roles in exoplanet studies. It provides access to a spectral range that can not be achieved from the ground and can characterize the detected planets in terms of atmospheric composition and effective temperature. Sensitive technology has already been proven for missions like JWST, SIM, and Spitzer, and within NASA's preliminary studies of TPF*



New Worlds Technology Development Program

To achieve New Worlds objective – studying nearby, habitable exoplanets - need preliminary observations before choosing a flagship mission:

– Planetary demography over wide range of conditions:

- Kepler, WFIRST, integrated ground-based program

– Measurement of zodiacal light:

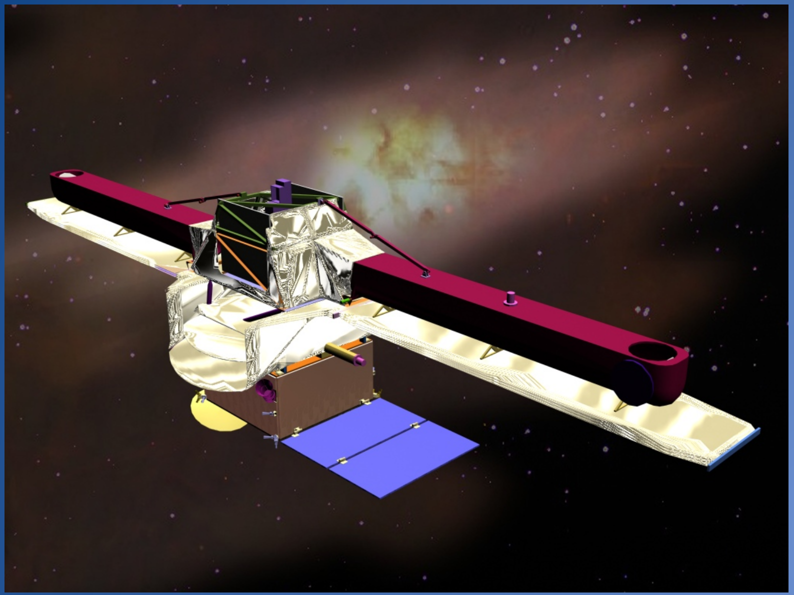
- Ground-based telescopes.
- Sub-orbital and explorer mission opportunities.

In parallel, need technology development for *competing approaches* to make informed choice in second half of decade

RECOMMEND $100-200M over decade

Planned integrated ground-space exoplanet program

A Small Structurally Connected Interferometer;
The Fourier-Kelvin Stellar Interferometer (FKSI) Mission



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Technologies:

- Infrared space interferometry
- Large cryogenic infrared optics
- Passive cooling of large optics
- Mid-infrared detectors
- Precision cryo-mechanisms and metrology
- Precision pointing and control
- Active and passive vibration isolation and mitigation

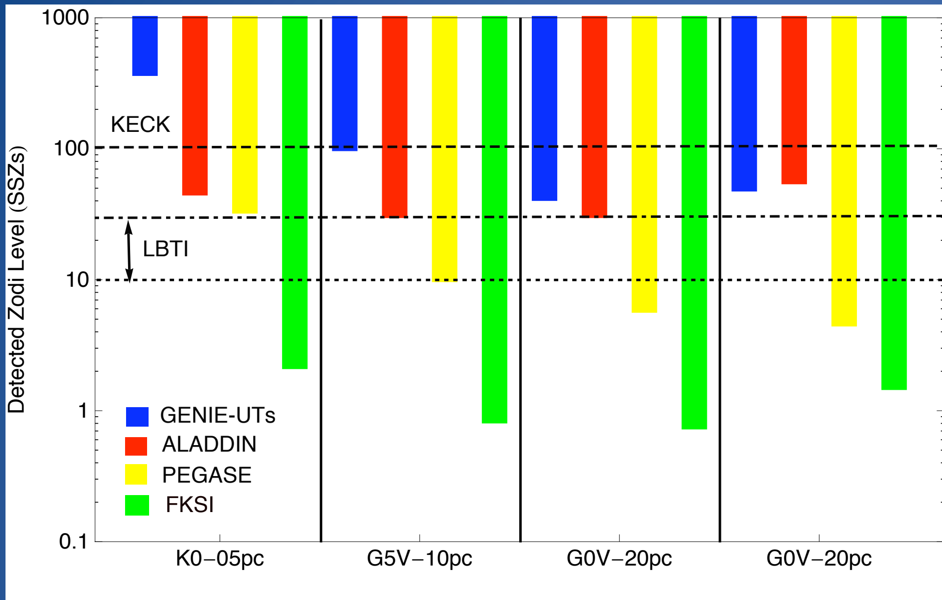
Key Science Goals:

- **Observe Circumstellar Material**
  - Exozodi measurements of nearby stars and search for companions
  - Debris disks, looking for clumpiness due to planets
- **Detect >20 Extra-solar Giant Planets**
  - Characterize atmospheres with R=20 spectroscopy
  - Observe secular changes in spectrum
  - Observe orbit of the planet
  - Estimate density of planet, determine if rocky or gaseous
  - Determine main constituents of atmospheres
- **Star formation**
  - Evolution of circumstellar disks, morphology, gaps, rings, etc.
- **Extragalactic astronomy**
  - AGN nuclei

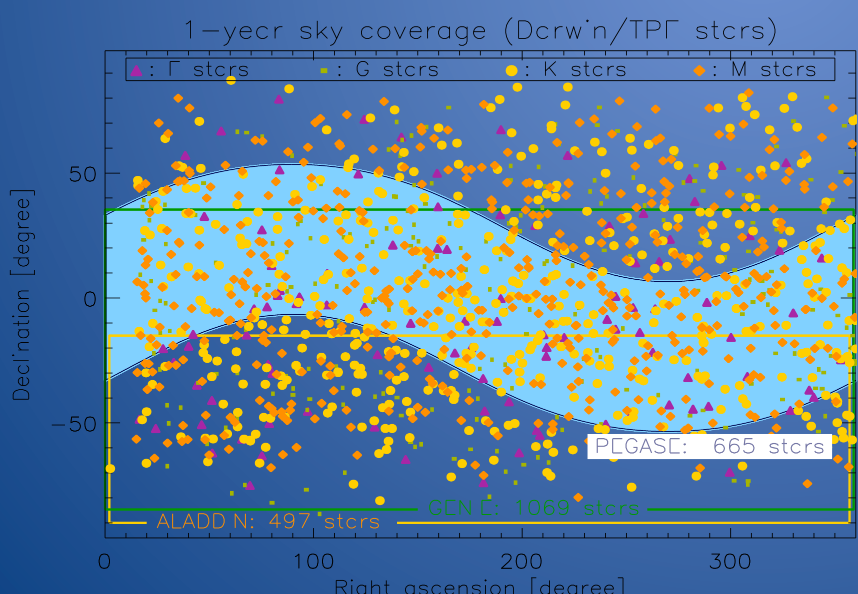
Key Features of Design:

- ~0.5 m diameter aperture telescopes
- Passively cooled (<70K)
- 12.5 m baseline
- 3 – 8 um (or 10 TBR) micron science band
- 0.6-2 micron band for precision fringe and angle tracking
- Null depth better than 10^-4 (floor), 10^-5 (goal)
- R=20 spectroscopy on nulled and bright outputs of science beam combiner

Debris Disk Sensitivity



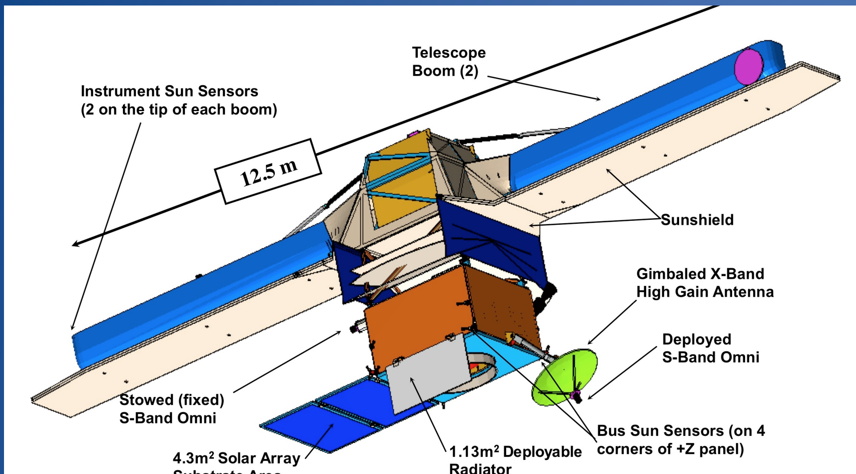
Expected performance for Pegase and FKSI compared to the ground-based instruments (for 30 min integration time and 1% uncertainty on the stellar angular diameters).

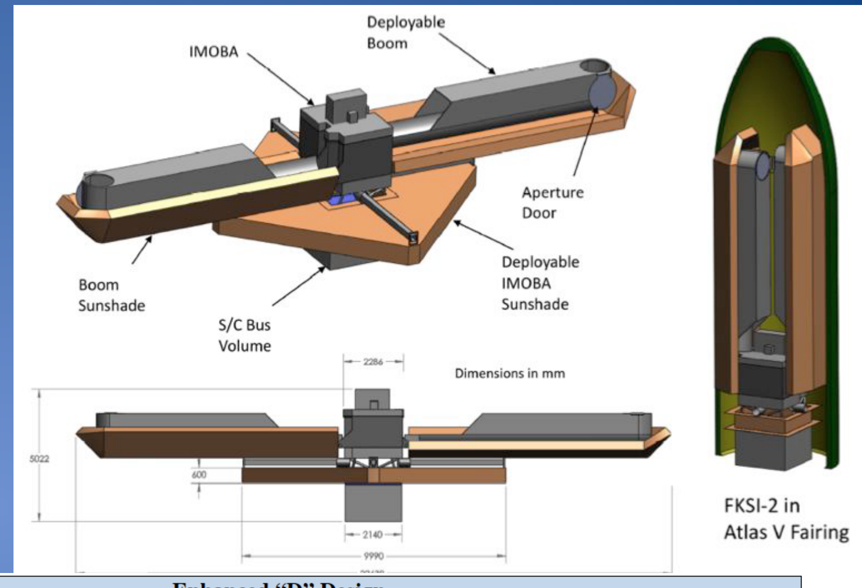


Sky coverage after 1 year of observation of GENIE (dark frame), ALADDIN (light frame) and Pegase (shaded area) shown with the Darwin/TPF all sky target catalogue. The blue-shaded area shows the sky coverage of a space-based instrument with an ecliptic latitude in the [-30˚, 30˚] range (such as Pegase). The sky coverage of FKSI is similar to that of Pegase with an extension of 40˚ instead of 60˚.

See Defrere et al. A&A (2008).

Enhanced FKSI Design





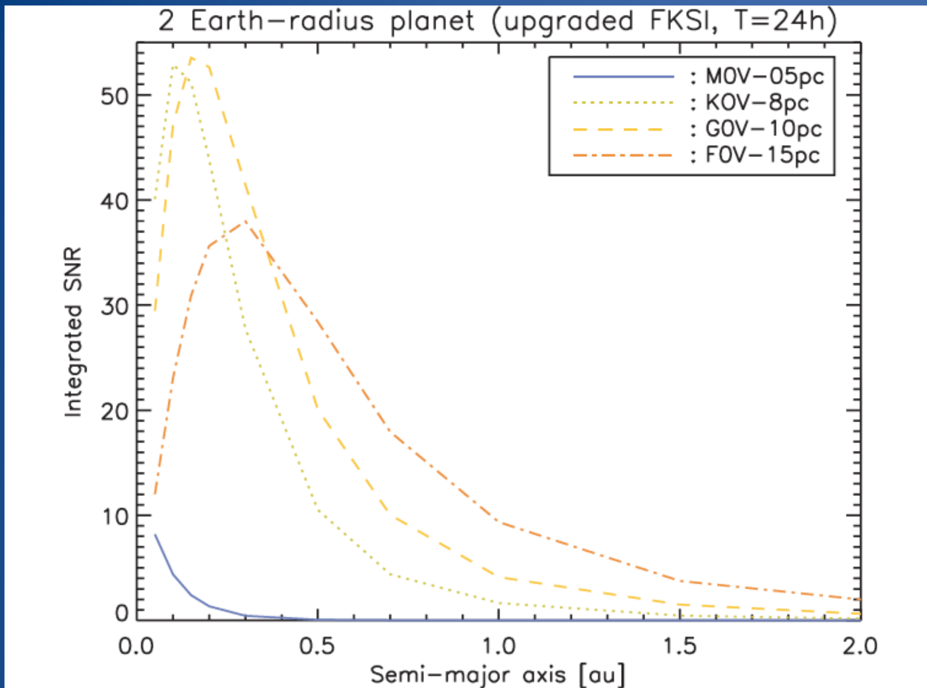
Basic Assumptions:
SNR = 5 for detection
SNR = 10 for spectroscopy (R = 20 at 10 μm)
3 sets of observations per star (visits)
< 2 years total
< 7 days total per star
T_{earth} = 288 K
Earth albedo = 0.3
Inclination angle of planet orbit = 45°
Sunshade FOR = ± 45°
1 SSZ emission from observed system's dust disk

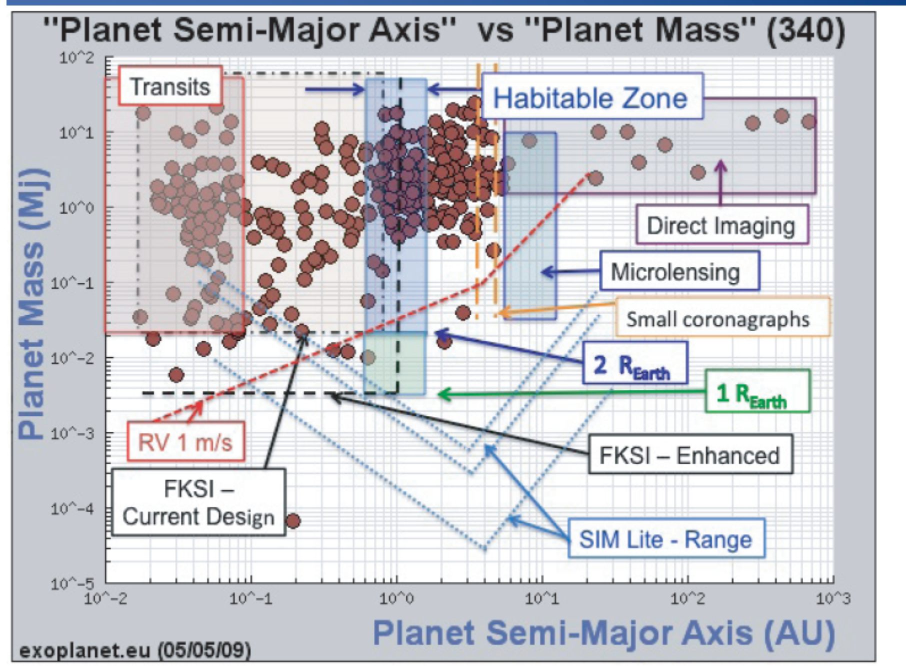
Enhanced "D" Design Tel = 1 m					
R_{Planet}	Total	N_F	N_G	N_K	N_{Spec}
1 R_{Earth}	4	0	1	3	4
2 R_{Earth}	34	6	16	12	16
Tel = 1.5 m					
1 R_{Earth}	15	0	7	8	4
2 R_{Earth}	95	35	48	12	27
Tel = 2.0 m					
1 R_{Earth}	29	3	14	12	12
2 R_{Earth}	138	65	61	12	43

Results of simulations using the TPF performance simulator of Dubovitsky & Lay for an enhanced FKSI but with 1-, 1.5-, and 2-m diameter telescopes. N_X is the number of 1 or 2 R_{Earth} exoplanets detected in the population of F, G and K dwarf stars within 30 pc. N_{spec} are the number of these target planets for spectroscopic characterization of the atmosphere.

Danchi, Barry 2010 SPIE

Enhanced FKSI Exoplanet Discovery Space





Simulations of FKSI performance with 1-2 m class telescopes at 40K and a 20-m baseline demonstrate that many 2 Rearth super-Earths and a few Earth-twins can be discovered and characterized within 30 pc of the Sun.

Discovery space for exoplanets for FKSI and other mission concepts and techniques

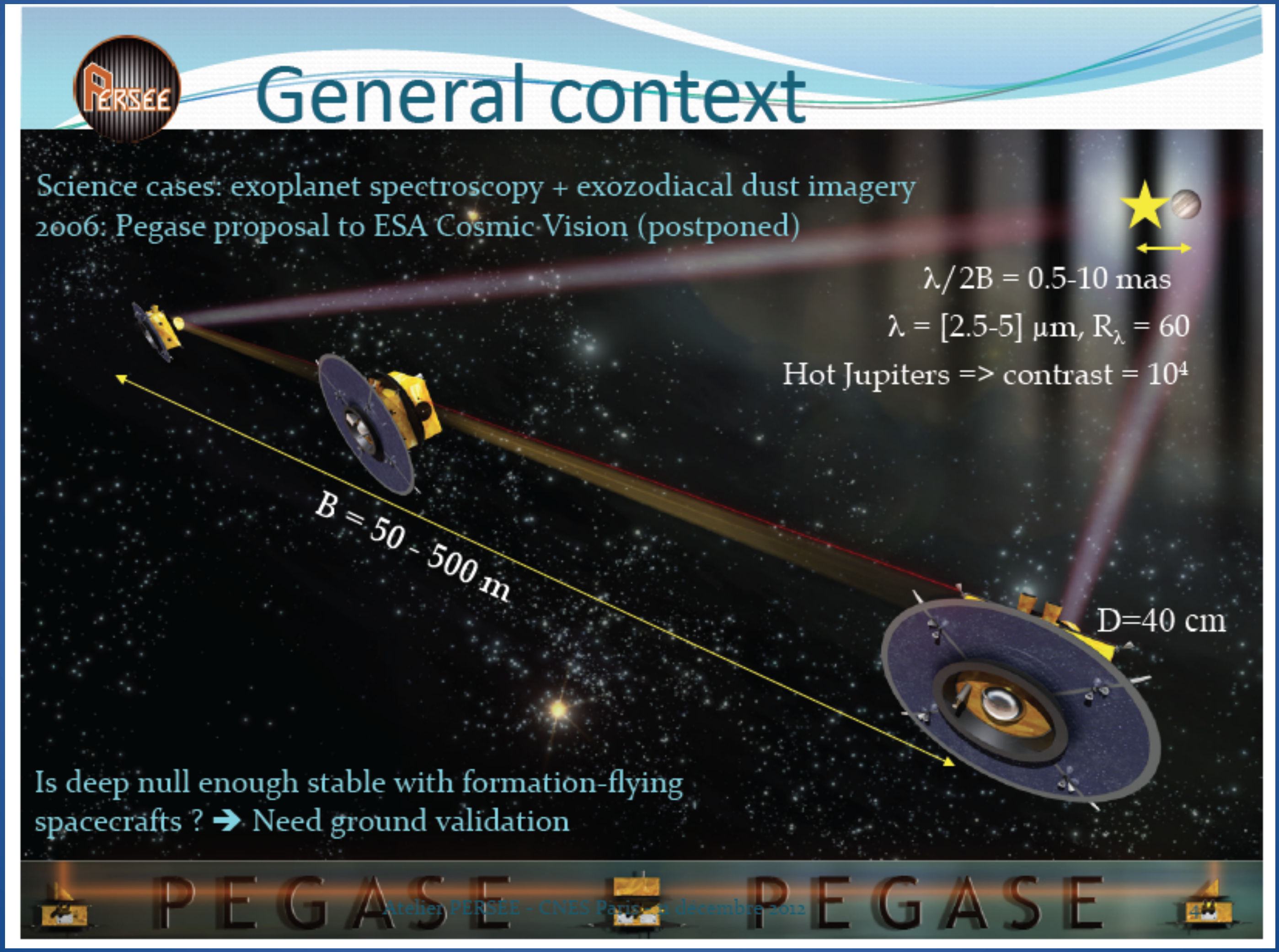
FKSI

- Most recent work in 2009-2010 time frame – mission design studies:
  - Center wavelength from 5 to 10 μm
  - Baseline from 12.5 m to 20 m
  - Mirror diameter from 0.5 m to 1.0 m
  - Passive cooling to 40 K
  - JWST cryocooler for detectors operating at longer wavelengths
  - Did performance calculations to see how many super-Earths and Earth-sized planets could be detected
  - Work was published in SPIE in 2010, and other conference proceedings
- Currently working with **PERSEE** for FKSI related issues:
  - Test imaging capabilities with realistic scene consisting of star, planet, and exozodi
  - Test of pathlength control for realistic boom and reaction wheel noise sources

Executive Summary
Workshop on the future of the bank PERSEE
Tuesday, December 11, 2012

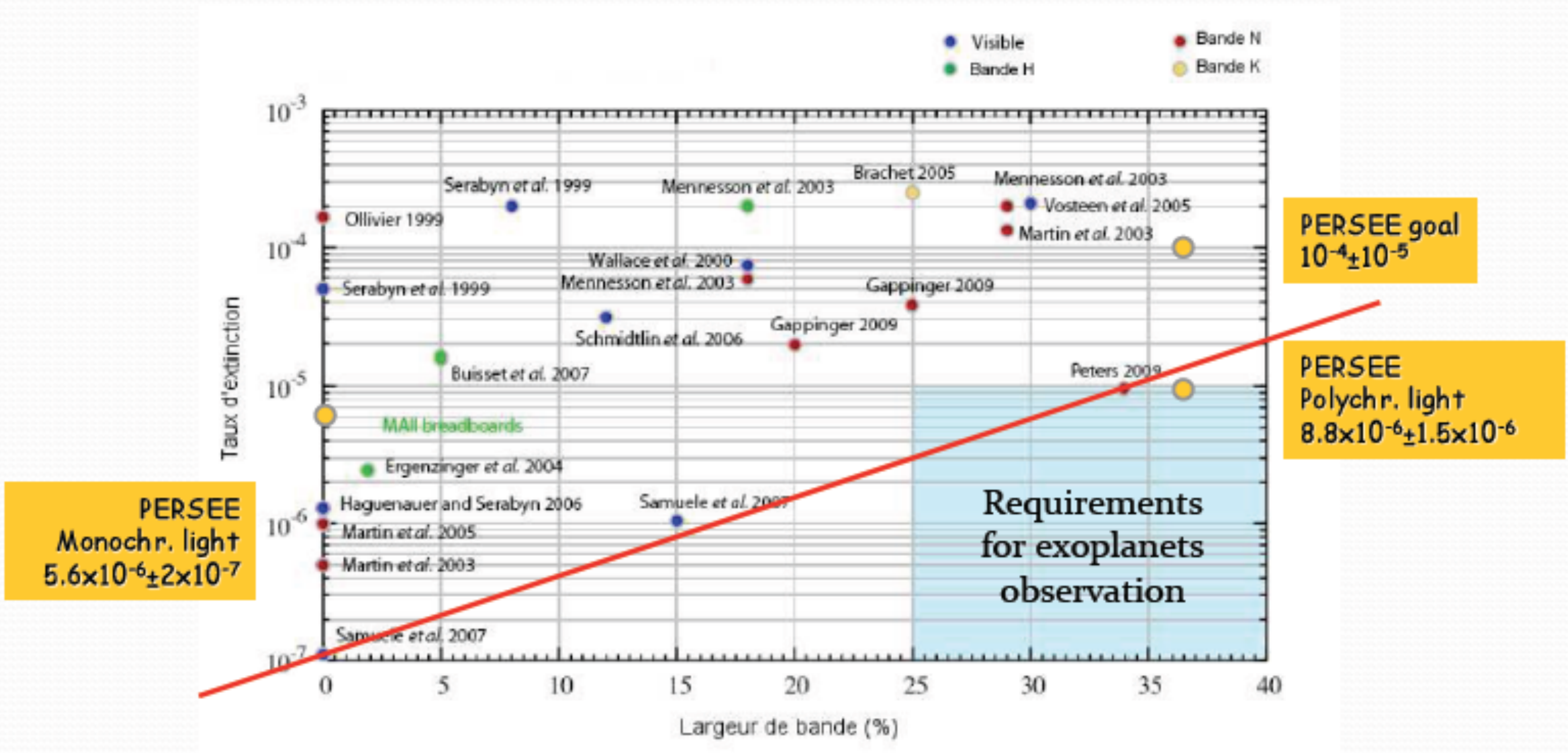
Version 0.1
We participated in the workshop:
• Vincent Coudé du Foresto, Raphael Galicher, Sophie Jacquinod, Emilie Lhome, Jean-Reess Michel, Daniel Rouan, Gérard Rousset, Didier Tiphène (Obs. Paris - LESIA)
• Jacques Berthon Olivier La Marle (CNES)
• Bruno Lopez, Jean-Luc Menut, Aurélie Marcotto, Florentin Millour (OCA)
• Jean-Baptiste Daban, Gaetan Dalla Vedova, Romain Petrov (U. Nice)
• Frédéric Cassaing Beatrice Sorrento (ONERA)
• Alain Léger, Marc Ollivier (IAS)
• Samuel Heidmann, Francois Henault, Pierre Kern, Guillermo Martin (IPAG)
• Peter Schuller (U. Cologne)
• Amandine Caillat (OAMP)
• Michel Tallon (Obs. Lyon)
• Bill Danchi (NASA Goddard)
• Julien Lozi (for Skype)
• Olivier Absil (U. Liege)
• Adrian Belu
The papers presented at this meeting are available online at:
http://www.lesia.obspm.fr/persee/forum-11-decembre/article/programme

French (CNES) PEGASE mission concept



From CNES meeting

Worldwide performances



From CNES meeting

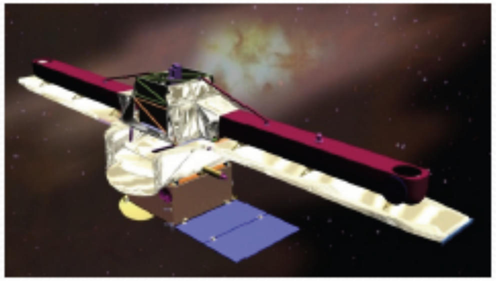
Conclusions and perspectives

Already done

- PERSEE achieves very efficient polychromatic null in non-polarized light
- LQG control loop maintains OPD at less than 1nm rms in presence of representative disturbances induced by reaction wheels (high frequency) with a significant amplitude

Still to be done

- Fringes acquisition with a initial drift speed (150µm/s) ➔ *in progress*
- Simulated complex targets (star + faint planet + exozodi) ➔ *PhD starting*
- Simulation of FKSI disturbances ➔ *coming soon ?*



Technology Investments

Technology	Cost
SIM Technology up to Phase B	$600 M
Keck Interferometer	$120 M
LBTI	$20 M +
JPL Testbeds (AcNT, AdNT, PDT, etc.)	$60 M
TOTAL	$800 M +

A number of smaller mission concepts and testbeds, such as FKSI, PICTURE, SPIRIT and WIIT testbed, BETTII, and Nulling Coronagraph Testbed(s), also have contributed, at the cost of $10 M+

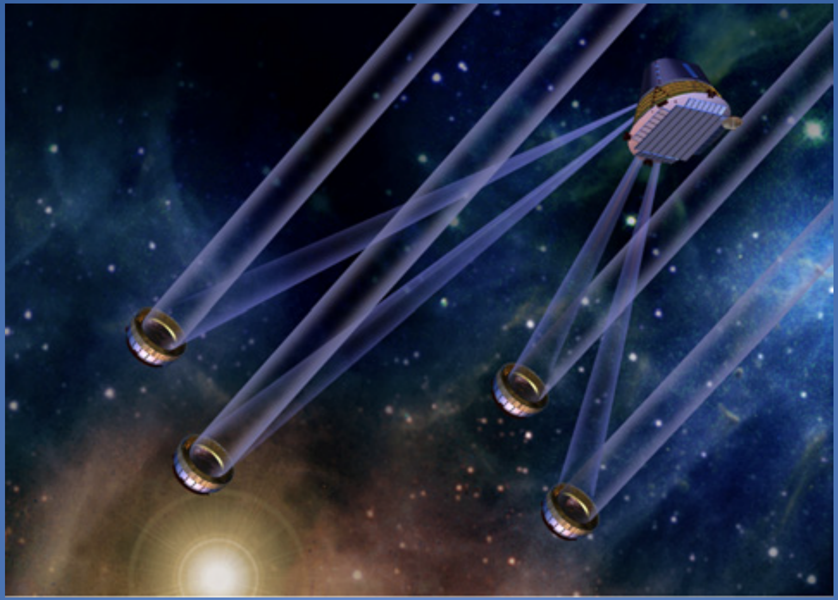
ARE WE GOOD STEWARDS OF THE TAXPAYER'S MONEY WHEN WE HAVE NO MISSION IN THE QUEUE BASED ON THESE INVESTMENTS?

Where do we go from here?

- Need to examine the state of the art for IR interferometry in space and assess the feasibility of a low-cost explorer, midex, or probe mission
- The Technical Readiness Levels for most all of the needed technologies are at 6 or above, with a few exceptions, given the completion of the testbeds and JWST technologies
- Design studies are needed to clarify cost and the few remaining technologies needed
- Interest from Europe for international collaborations is still strong
- Need to find new creative ways to work together within NASA itself and to foster international collaboration
- It would be beneficial to open LBTI to broader NASA science given the cutoff of funding to the Keck Interferometer
- Need continued support from US exoplanet community and HQ for further work in this area
- Consequence of no action or a lack of a commitment to move forward on a concrete mission will be a withering of the field in the time frame of ~ 5 years (especially after LBTI exozodi activity ends)

Backup

TPF-I Technology Goals and Accomplishments



- Architecture
  - Adoption of Emma X-array by TPF-I and Darwin as basis for mission design
  - Demonstration of agreement between independent performance models of Emma X-Array and comprehensive target star catalog

Technical Readiness for a Small Structurally Connected Interferometer

Item	Description	TRL	Notes
1	Cryocoolers	6	Source: JWST
2	Precision cryogenic structure (booms)	6	Source: JWST
3	Detectors (near-infrared)	6	Source: HST, JWST Nircam
4	Detectors (mid-infrared)	6	Source: Spitzer IRAC, JWST MIRI
5	Cryogenic mirrors	6	Source: JWST
6	Optical fiber for mid-infrared	4	Source: TPF-I
7	Sunshade	6	Source: JWST
8	Nuller Instrument	4-5	Source: Keck Interferometer Nuller, TPF-I project, LBTI
9	Precision cryogenic delay line	6	Source: ESA Darwin

*Note: The requirement for the FKSI project is a null depth of 10^{-4} in a 10% bandwidth. Laboratory results with the TPF-I testbeds have exceeded this requirement by an order of magnitude (Lawson et al. 2008).

Cost Estimates

Over the years we have done grassroots, PRICE H, and Resource Analyst Office parametric estimates:

- *Cost is $635 M for a 2 year minimum science mission, including $160 M for LV*
- *Thus it is $475 M without LV, well below guidance of $600-800 M without LV*
- *This is at 50% probability on the "S" curve*
- *At 70%, cost estimate is $600 M without LV*

- We have around $100-200 M for mission growth while remaining within cost box.
  - *Desirable trades include increasing apertures to 1m, telescopes to 40K, and wavelength range from 5-15 um, baseline to 20 m.*

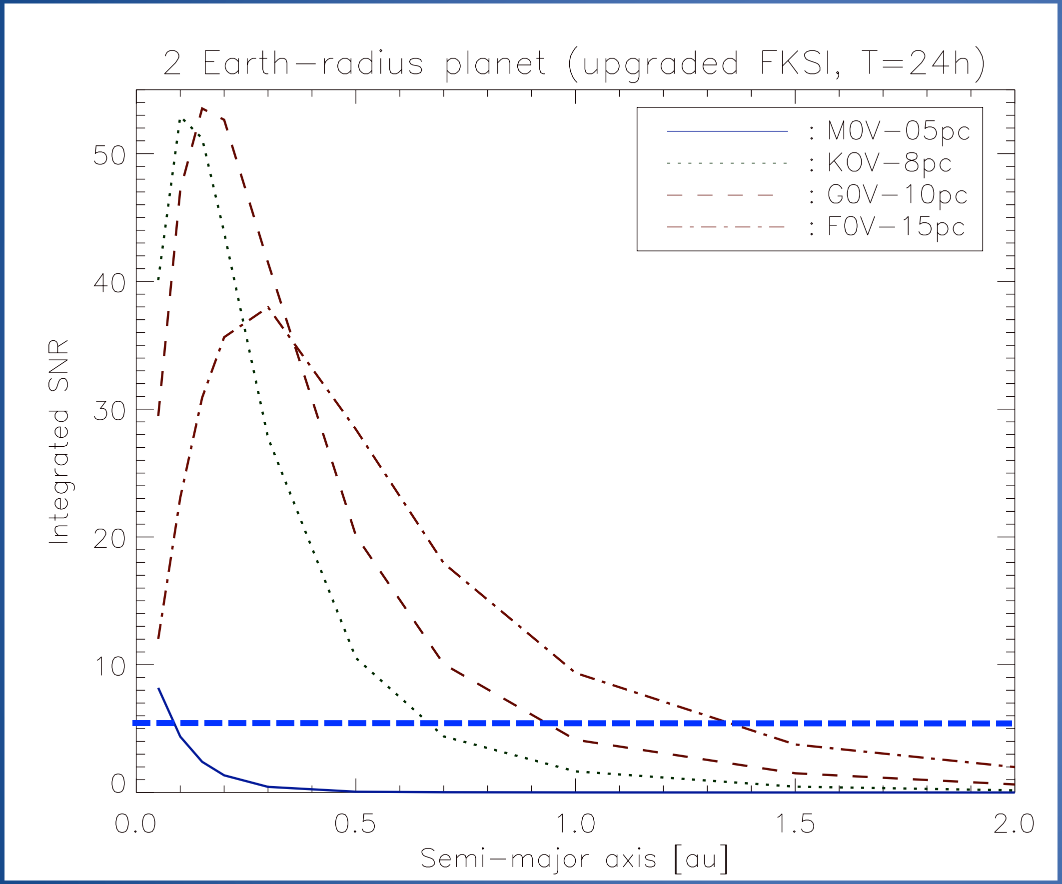
Recent Design Studies: Enhanced FKSI

Current design		Enhanced design	
Telescope diameter	0.5 m	Telescope diameter	from 1 to 2 m
Baseline	12.5 m	Baseline	20 m
Wavelength range	from 3 to 8 µm	Wavelength	from 5 to 15 µm
Telescope temperature	down to 60 K	Telescope temperature	down to 40 K

Current design		Enhanced design	
Field of regard / Sun shade	+/- 20 °	Field of regard / Sun shade	> +/- 45 °

Upgraded FKSI Detects many more Super-Earths, R>2 R_{Earth}

1 m apertures, 40K telescopes, 20 m baseline



SNR > 5

- F0V R<1.35 AU
- G0V R<0.95 AU
- K0V R<0.55 AU
- M0V R<0.1 AU

Defrere et al. 2009

Recent Performance Study Results

Basic Assumptions:

- SNR = 5 for detection
- SNR = 10 for spectroscopy
  (R = 20 at 10 μm)
- 3 visits
- < 2 years total
- < 7 days total per star
- T_{earth} = 288 K
- Earth albedo = 0.3
- Inclination angle of planet orbit = 45°
- Sunshade FOR = +/- 45°
- 1 Solar System Zodi Exozodi

Ref: Dubovitsky & Lay 2004
Danchi, Lopez et al. 2009

Enhanced design
Tel = 1 m

R_{Planet}	Total	N_F	N_G	N_K	N_{Spec}
1 R_{Earth}	4	0	1	3	4
2 R_{Earth}	34	6	16	12	16

Tel = 1.5 m

R_{Planet}	Total	N_F	N_G	N_K	N_{Spec}
1 R_{Earth}	15	0	7	8	4
2 R_{Earth}	95	35	48	12	27

Tel = 2.0 m

R_{Planet}	Total	N_F	N_G	N_K	N_{Spec}
1 R_{Earth}	29	3	14	12	12
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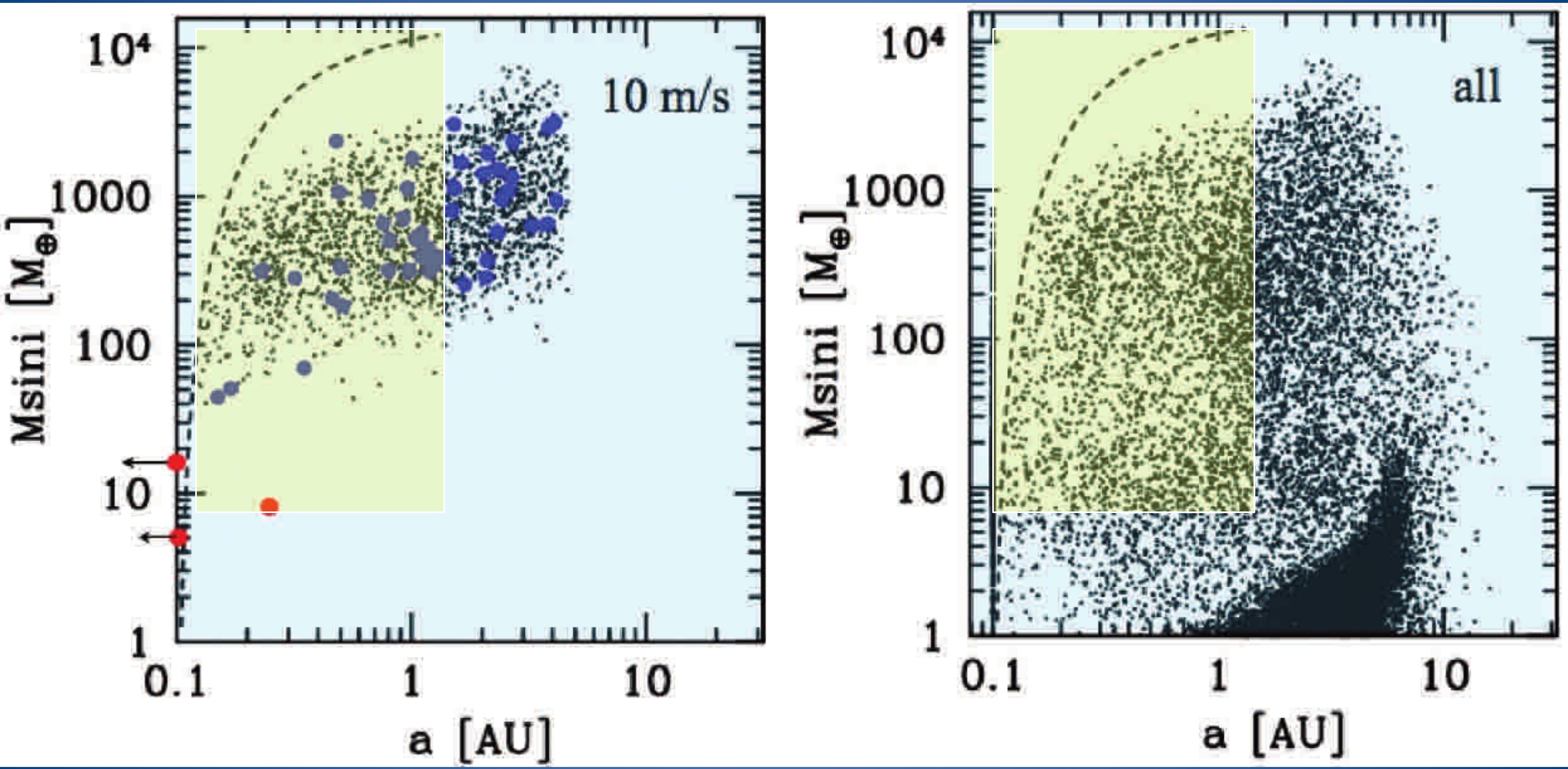
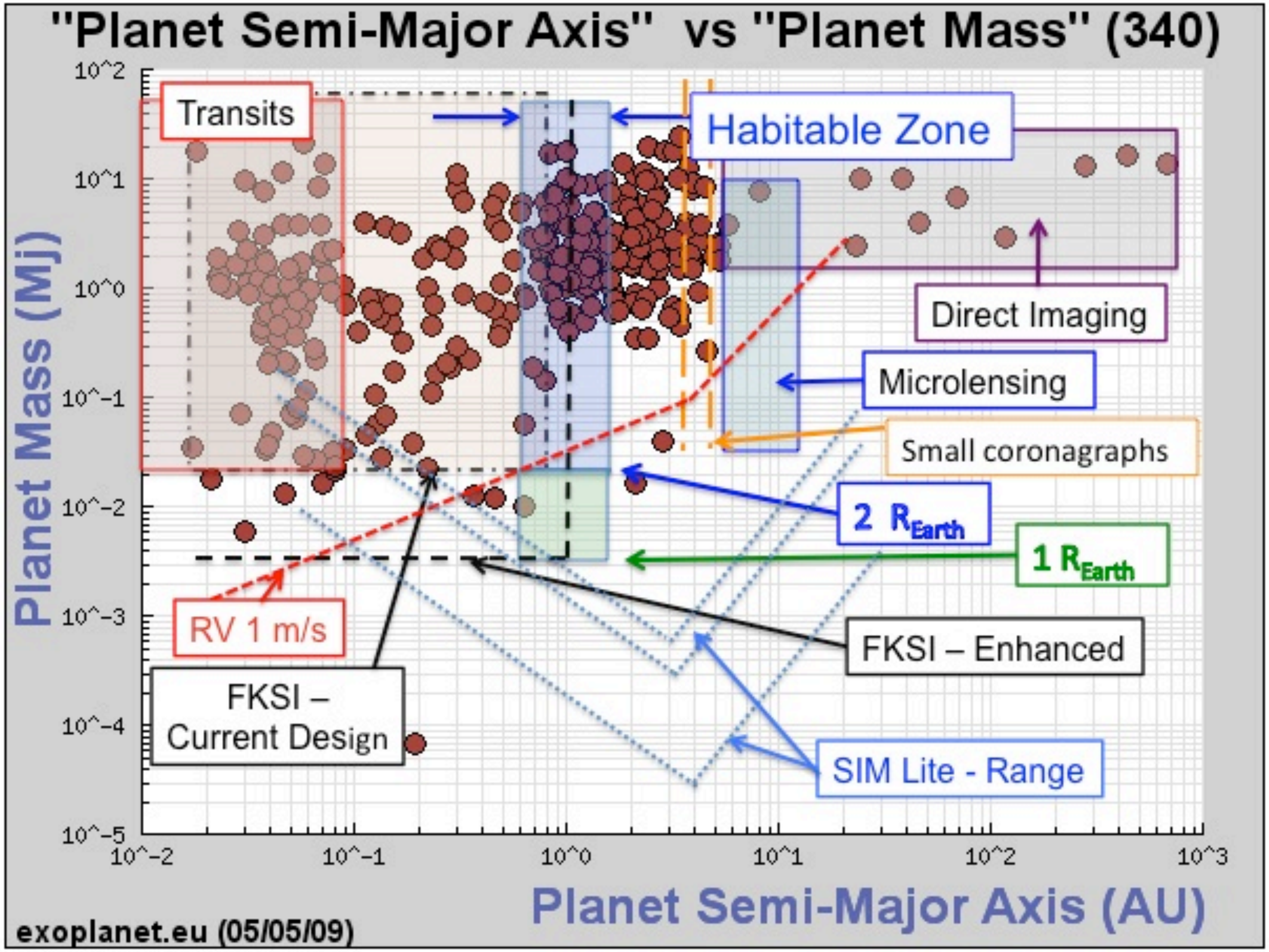
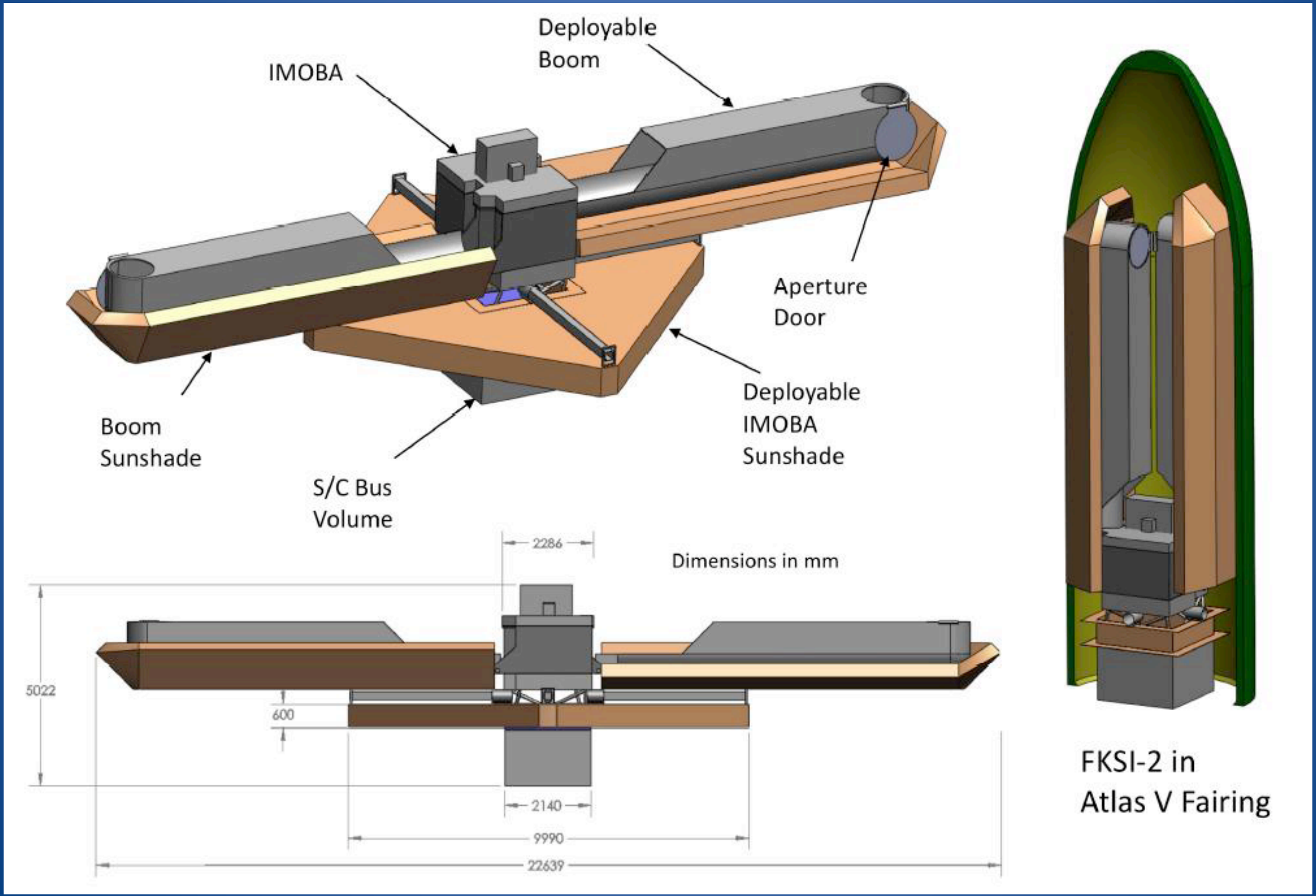
Enhanced Discovery Space For Super Earths with upgraded FKSI



FKSI Characterization/Discovery Space for Exoplanets



Preliminary Mechanical Design for Enhanced FKSI



More Recommendations on R&A Support

- ***Theory support:***
  - *We will require sustained support of strong astrobiology and atmospheric chemistry programs.*
- ***Agency Coordination & Programmatic Strategy***
  - *NASA and NSF goals, makes it an ideal topic for coordination between the agencies, and we urge NASA and NSF staff to leverage this relationship to cover the full breadth of exoplanet science and technology*
- ***International Coordination, Collaboration, & Partnership***
  - *The relationships forged between US and European collaborators should be fostered during the next decade for further studies of small mission and flagship mission concepts. A new letter of agreement is necessary to further future collaborations.*